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Editorial

Water reuse, food production and public health: Adopting transdisciplinary, systems-based approaches to achieve water and food security in a changing climate

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ABSTRACT

Climate change and population growth are contributing to a growing global freshwater crisis that is exacerbating agricultural water scarcity and compromising food security and public health. In light of these challenges, the increased reliance on nontraditional irrigation water sources, such as reclaimed or recycled water, is emerging as a potentially viable strategy to address water and food insecurity worldwide. This editorial provides an overview of the global need for agricultural water reuse and outlines the environmental and public health impacts associated with this practice. Policy implications, including an emphasis on "One Water" approaches, are discussed. Finally, the editorial leads off a Special Issue that includes a collection of articles reporting on the initial research and extension/outreach findings of CONSERVE: A Center of Excellence at the Nexus of Sustainable Water Reuse, Food and Health, funded by the U.S. Department of Agriculture, National Institute of Food and Agriculture. Taken together, this compilation of articles addresses the overarching theme that transdisciplinary teams are key with regard to moving the science of agricultural water reuse forward to achieve water and food security and advance public health in a changing climate.

The planet is in the midst of a growing freshwater crisis that is compromising food security and public health. While 70% of the Earth's surface is covered in water, over 96% of this water is retained in saline oceans, with only 2.5% remaining in freshwater reserves (including glaciers, icecaps, groundwater and surface water) (USGS, 2016). Altogether, this means that < 1% of Earth's water is readily available for human use including domestic activities and agriculture (USGS, 2016). Meanwhile, the agricultural sector accounts for 70% of total freshwater withdrawals worldwide (World Bank Group, 2016; USGS, 2016), and climate change (USGCRP, 2017) along with population growth are exacerbating agricultural water scarcity challenges in multiple regions of the world. For example, an estimated 56% of global irrigated cropland is located in regions under high or extremely high water stress (Gassert et al., 2013; Intriago et al., 2018). Making matters worse, a recent satellite-based study of Earth's freshwater resources demonstrated that Earth's dry areas are increasingly drier, while wet areas are getting wetter (Rodell et al., 2018), a scenario that was predicted for the *end* of the 21st century by the Intergovernmental Panel on Climate Change. These dire circumstances call for the urgent need to explore and adopt safe, alternative, water-saving irrigation strategies to safeguard water security and sustain food production across the globe.

In light of the above mentioned exigencies, food crop irrigation with nontraditional irrigation water sources, including advanced treated municipal wastewater (also referred to as reclaimed or recycled water), return flows and brackish waters, (Dery et al., 2018; USDA, 2017) has emerged as a potentially viable strategy to address agricultural water shortages in multiple countries (Levine and Asano, 2004; Tal, 2016). Most notably, in Israel, the world's leader in water reuse, approximately 86% of domestic advanced treated wastewater, equaling 400 million m^3, is reclaimed and used for agricultural irrigation (Kershner, 2015; Tal, 2016). Moreover, there is evidence that another sixty countries engage in some form of wastewater (treated and untreated) irrigated agriculture. However, this number is likely underestimated because, for the majority of countries, data on the quantities of wastewater produced, treated and reclaimed are unavailable, partial or outdated (Sato et al., 2013; Scott et al., 2004; Thebo et al., 2017).

There are multiple environmental benefits associated with the agricultural reuse of advanced treated wastewater including: reduced pressures on overstressed aquifers (Eslamian, 2016; Intriago et al., 2018; Parsons et al., 2010); successful groundwater recharge (Angelakis and Durham, 2008; Jaramillo and Restrepo, 2017); reductions in fertilizer applications and expenses due to nutrients remaining in reclaimed water (Drechsel et al., 2010; Jaramillo and Restrepo, 2017; Lyu et al., 2016); and higher crop yields for some crop types that are grown with reused water (Intriago et al., 2018; Vergine et al., 2017; Vivaldi et al., 2013). When water reuse applications are paired with advanced, water-saving, drip irrigation technologies, including subsurface irrigation and sensor-based, "irrigation on demand" systems, the impacts on water conservation and overall crop production can be remarkable. In the past six decades, Israel has experienced a 1600% increase in the economic value of produce generated by Israeli farmers (Kislev and Tsaben, 2013; Tal, 2016), an increase largely attributed to government land management policies, as well as the widespread use of both drip irrigation technologies and reclaimed water. However, extensive and prolonged agricultural water reuse is not without environmental, soil health, plant health and potential public health risks that need to be further evaluated as water reuse practices expand.

Microbiological, chemical and physical contaminants remaining in reclaimed water, including pathogens (viral, bacterial and protozoal), antibiotic-resistant bacteria, sodium, chlorine, bicarbonate, heavy

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metals, plasticizers (e.g. phthalate esters and bisphenol A), as well as pharmaceuticals and personal care products (PPCPs) (Al-Saleh et al., 2017; Asgari and Cornelis, 2015; Goldstein et al., 2012, 2017; Jaramillo and Restrepo, 2017; Kulkarni et al., 2017; Goldstein et al., 2014a; Tal, 2016), have the potential to negatively impact soil, plant and public health. For instance, variations in the structure and magnitude of soil microbial biomass, as well as changes in the physicochemical parameters of soil, have been observed following irrigation with reclaimed water (Becerra-Castro et al., 2015). Most importantly, emerging data reflect that "signs of salinity damage from long-term effluent usage in Israel are everywhere," (Tal, 2016) with regard to both soil and plant health, and "Israel's policy of lower prices for salty water and absolute utilization of wastewater for irrigation without addressing salinity may have been reckless" (Raveh and Ben-Gal, 2016).

Moreover, while earlier epidemiological studies—focusing on farmers' and irrigators' exposures to pathogens, as well as subsequent gastrointestinal outcomes—identified little to no health effects associated with the agricultural reuse of *treated* wastewater (Durand and Schwebach, 1989; Fattal et al., 1986; Shuval et al., 1989), emerging exposure assessment studies are providing evidence that both chemical and microbiological contaminants persisting in treated wastewater used in irrigation activities may impact public health. For example, pharmaceutical compounds remaining in reclaimed water, such as lamotrigine and carbamazepine, are capable of uptake and transport in crops, and have been detected in both the edible portion of reclaimed water irrigated plants and the urine of individuals who have eaten them (Ben Mordechay et al., 2018; Goldstein et al., 2018; Paltiel et al., 2016). Moreover, in terms of occupational exposures, recent studies from our group have shown that spray irrigators exposed to reclaimed water (tertiary treated wastewater) have an increased odds of colonization with emerging bacterial pathogens, including antibiotic-resistant coagulase-negative staphylococci (Goldstein et al., 2017; Goldstein et al., 2014b), suggesting that occupational exposures to certain types of reclaimed water may result in an increased risk of infection with these microorganisms. Given these findings, it is not only important to determine whether or not these emerging ingestion and occupational exposures result in subsequent acute, infectious and/or chronic human health impacts but also imperative to further evaluate the range of potential exposure pathways (Fig. 1) that may be experienced by consumers, farmers and secondary contacts as global agricultural water reuse continues to increase. The increased utilization of advanced analytical (e.g., high performance liquid chromatography-tandem mass spectrometry) and DNA sequencing technologies could support improved understanding of these exposure pathways.

To ultimately prevent exposures to chemical and microbiological contaminants that are known or suspected to persist in reclaimed water, innovations are necessary with regard to the development and implementation of cost-effective, energy-efficient water treatment technologies (both centralized and decentralized). These innovative treatment technologies will need to be designed to simultaneously remove a number of important contaminants, including viral, bacterial and protozoal pathogens; plasticizers; PPCPs; antibiotic resistance determinants; and salts, that may persist in reclaimed water utilized in irrigation applications. In addition, high-quality extension/outreach and education programs are necessary to share new knowledge with both agricultural and non-agricultural (consumers) communities, and address the concerns of different stakeholders with regard to agricultural water reuse. However, outreach and educational programming in this area can be challenging given existing scientific knowledge gaps; water quality, food safety and health concerns; misconceptions; and inaccurate public branding of recycled water (Dobrowolski et al., 2008). The involvement of experienced health and risk communicators in agricultural water reuse outreach programs could effectively help to improve environmental health literacy around these issues. Finally, increased understanding of the social, behavioral, economic and regulatory factors that influence agricultural water reuse is needed such that either existing country- and state-specific water reuse regulations can be bolstered or new regulations can be adopted.

To date, no country has comprehensive regulations that address emerging contaminants remaining in reclaimed water, such as PPCPs, antibiotic resistance determinants and endocrine disruptors. Even more concerning, some countries have no guidance or regulations on water reuse whatsoever, resulting in ongoing agricultural reuse of *raw or untreated* wastewater, a practice that is harmful to both the environment and public health (Ali et al., 2018; Falkenberg and Saxena, 2018; Khalid et al., 2018; Roohi et al., 2016). However, if agricultural water reuse is going to emerge on a global scale as a viable and sustainable solution for diverse populations to address water and food insecurity, closely enforced regulations and policies are imperative.

In particular, regulations and policies that embody the "One Water" approach—"the view that all water has value and should be managed in a sustainable, inclusive, integrated way" (U.S. Water Alliance, 2016)—must be embraced. This means that: 1) all water types, from raw source water for drinking water treatment plants to water flushed down toilets and drains should be viewed through the lens of "source water protection;" and 2) differing water types must ultimately be treated to established standards appropriate for their intended downstream applications. If we will need to rely more heavily on reclaimed water to grow our food, then we will all need to move towards an era that fully embraces "green chemistry" ("the utilization of a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacture and application of chemical products" (Anastas and Warner, 1998)) and mandates that the great majority of products, compounds (and their metabolites) that are permitted down drains are non-toxic, biodegradable, soil-friendly, and do not excessively elevate salt concentrations. These approaches can then enable less-costly, streamlined wastewater treatment approaches.

Again, Israel has taken initial steps in this regard through regulations enacted by the Ministry of Environment in 1994 that put controls on levels of salts allowed down the drain in order to reduce the ultimate salinity of treated wastewater (Tal, 2012, 2016). These efforts included controlling the use of salts in kosher slaughterhouses, discharging brines to the sea, and phasing in controls on domestic and industrial detergents that substantially reduced allowable levels of boron and sodium in these products (Tal, 2012; Weber and Juanico, 2004). Dramatic declines in both boron and sodium concentrations in treated wastewater ensued after these regulations were implemented in 1999 (Tal, 2012; Weber and Juanico, 2004). If we can emulate these approaches and achieve high-level "source water protection" for all water sources including those entering wastewater treatment plants, we can ultimately protect soil health, plant health and public health within a successful paradigm of agricultural water reuse.

Moving forward, in order to comprehensively address the knowledge gaps noted above and realize a "One Water" world supportive of "source water protection" and appropriate treatment for all water types, transdisciplinary, systems-based approaches that integrate research, extension/outreach and education, and include diverse stakeholders from academia, government, industry and the non-profit sector, are needed. Our team has embraced such an approach through CONSERVE: A Center of Excellence at the Nexus of Sustainable Water Reuse, Food & Health, which was established in 2016 through funding from the United States Department of Agriculture, National Institute for Food and Agriculture (USDA-NIFA) to the University of Maryland School of Public Health. A long-term goal of USDA-NIFA is to "solve critical water resource problems in rural and agricultural watersheds across the United States". Within this framework, CONSERVE employs a systems-based approach (Fig. 2) to evaluate the availability (quantity and quality) of nontraditional irrigation water sources (e.g. reclaimed water, brackish water, return flows) (Dery et al., 2018; USDA, 2017) that could be used to help farmers conserve groundwater; identify the socio-behavioral, economic and regulatory factors that impact the use of these sources; and develop, implement, and evaluate on-farm water

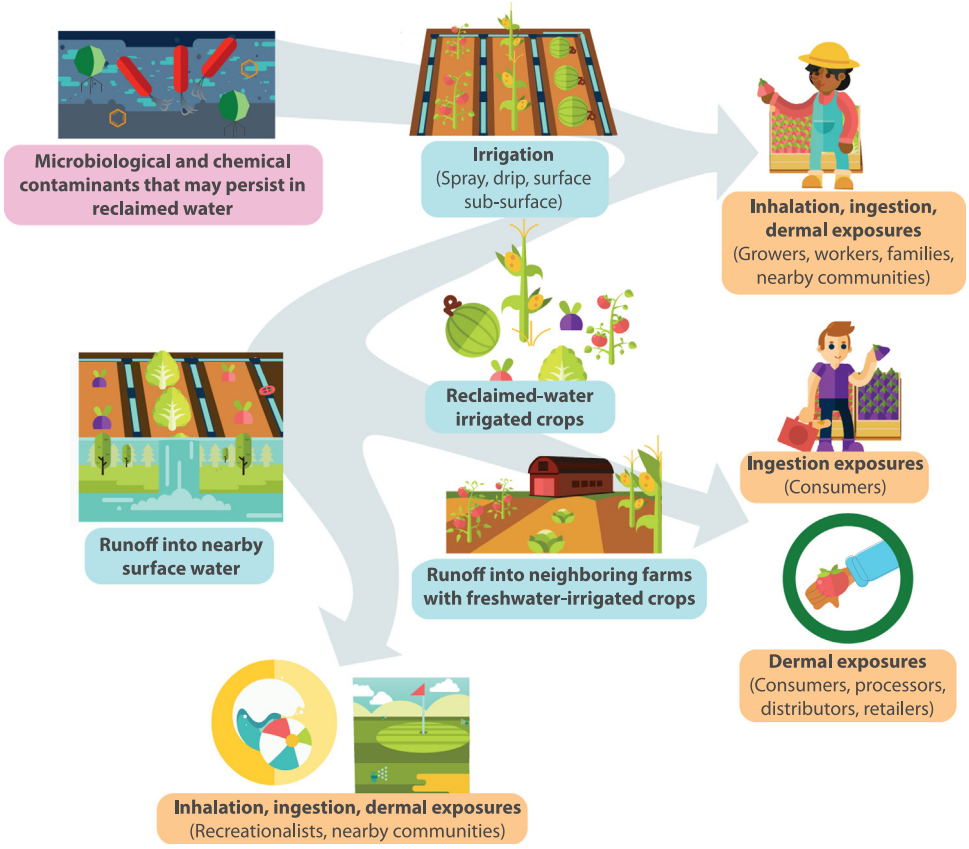

Fig. 1. Potential human exposures (highlighted in orange boxes) associated with the use of reclaimed water on food crops.

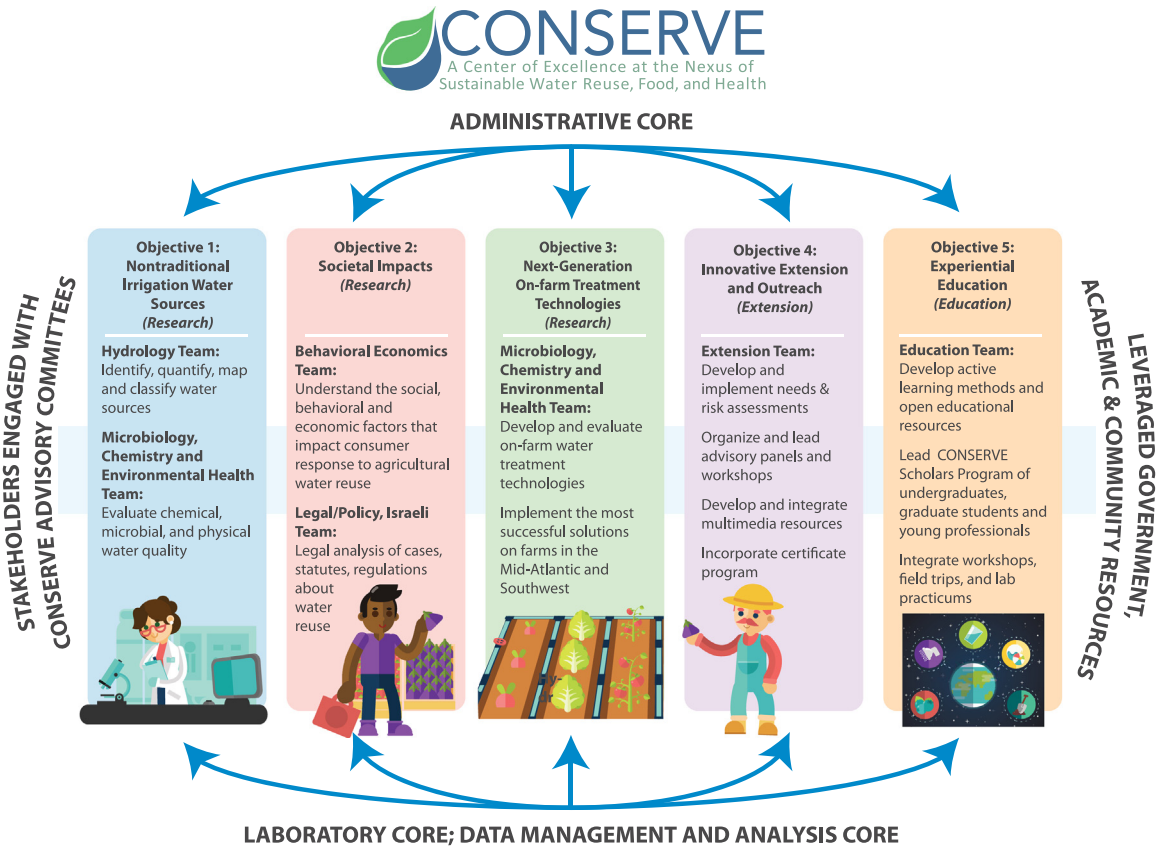
CONSERVE
A Center of Excellence at the Nexus of Sustainable Water Reuse, Food, and Health
ADMINISTRATIVE CORE
STAKEHOLDERS ENGAGED WITH CONSERVE ADVISORY COMMITTEES
LEVERAGED GOVERNMENT, ACADEMIC & COMMUNITY RESOURCES
Objective 1: Nontraditional Irrigation Water Sources (Research)
Hydrology Team: Identify, quantify, map and classify water sources
Microbiology, Chemistry and Environmental Health Team: Evaluate chemical, microbial, and physical water quality
Objective 2: Societal Impacts (Research)
Behavioral Economics Team: Understand the social, behavioral and economic factors that impact consumer response to agricultural water reuse
Legal/Policy, Israeli Team: Legal analysis of cases, statutes, regulations about water reuse
Objective 3: Next-Generation On-farm Treatment Technologies (Research)
Microbiology, Chemistry and Environmental Health Team: Develop and evaluate on-farm water treatment technologies
Implement the most successful solutions on farms in the Mid-Atlantic and Southwest
Objective 4: Innovative Extension and Outreach (Extension)
Extension Team: Develop and implement needs & risk assessments
Organize and lead advisory panels and workshops
Develop and integrate multimedia resources
Incorporate certificate program
Objective 5: Experiential Education (Education)
Education Team: Develop active learning methods and open educational resources
Lead CONSERVE Scholars Program of undergraduates, graduate students and young professionals
Integrate workshops, field trips, and lab practicums
LABORATORY CORE; DATA MANAGEMENT AND ANALYSIS CORE

Fig. 2. The transdisciplinary, systems-based approach of CONSERVE: A Center of Excellence at the Nexus of Sustainable Water Reuse, Food & Health.

treatment technologies that can enable the safe and successful use of nontraditional irrigation water. We then share this new knowledge with agricultural and non-agricultural communities, and employ experiential education to teach, train, and inspire future water reuse leaders. Our diverse team includes researchers, extension/outreach specialists, and educators from nine different institutions in two U.S. regions, the Mid-Atlantic and the Southwest, as well as collaborators from Israel's Arava Institute for Environmental Studies. We continually seek to partner with water reuse leaders from academia, government, industry and non-profit sectors and have recently begun collaborations with a multi-disciplinary team of researchers at the Hebrew University of Jerusalem.

In this Special Issue of *Environmental Research*, the collection of articles report on the initial research and extension/outreach findings from CONSERVE, and cover topics such as 1) microbiological and chemical contaminants that persist in nontraditional irrigation water sources; 2) farmer and consumer perspectives on the use of nontraditional irrigation water on food crops; and 3) emerging on-farm water treatment technologies that can be used to improve the quality of nontraditional irrigation water sources. Together, these articles address the overarching theme of how transdisciplinary teams can move the science of agricultural water reuse forward to achieve water and food security and advance public health in a changing climate.

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